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The Impact of Augmented Reality Media on High School Students' Critical Thinking Skills in Physics

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Abstract – *The rapid development of digital technologies has created new opportunities to enhance learning processes in science education, particularly in physics, which is often perceived as abstract and conceptually difficult. Students frequently struggle to interpret invisible phenomena such as electric charges and fields, leading to misconceptions that hinder higher-order thinking skills. In response to this challenge, augmented reality (AR) has emerged as a promising instructional tool capable of visualizing abstract concepts and fostering active engagement. This study aimed to investigate the effect of AR-based learning media on students' critical thinking skills in high school physics. A quasi-experimental design with a posttest-only nonequivalent control group was employed, involving two intact Grade XII classes: the experimental group (n = 32) received instruction using PyLo-AR, while the control group (n = 33) was taught through conventional methods. Data were collected using a validated essay test that measured four critical thinking indicators: interpretation, analysis, evaluation, and inference. The results of descriptive analysis showed that the experimental group achieved a higher mean score (M = 14.56, SD = 2.03) compared to the control group (M = 12.94, SD = 1.95). Inferential analysis using the independent samples t-test indicated a statistically significant difference between the groups (p = 0.002), confirming the effectiveness of AR-based instruction. The novelty of this research lies in its focus on critical thinking outcomes rather than solely on conceptual understanding or motivation. In conclusion, AR-based media not only improve students' mastery of abstract physics concepts but also strengthen their critical thinking skills, offering meaningful contributions to the advancement of physics education in the twenty-first century.*

Keywords: *augmented reality; critical thinking skills; digital learning media; electrostatics; physics education*

I. INTRODUCTION

Physics, as one of the fundamental sciences, plays a critical role in shaping students' logical reasoning, problem-solving abilities, and understanding of natural phenomena. Nevertheless, physics is often considered difficult because many of its concepts are highly abstract and cannot be directly observed, leading to persistent misconceptions among students. Several studies have emphasized that students frequently face challenges in interpreting and applying physics concepts, particularly when learning depends heavily on memorization and limited exposure to visualization (Rachmawati & Wiyatmo, 2025). Such conditions hinder the development of higher-order thinking skills, especially critical thinking, which is regarded as one of the essential competencies in the twenty-first century.

The urgency to enhance critical thinking in physics education has been widely recognized. Critical thinking involves the capacity to interpret, analyze, evaluate, and infer information to make reasoned judgments. In classroom practice, however, conventional teaching methods still dominate, with teachers relying primarily on lectures and textbook-based instruction. This mode of delivery often reduces students to passive recipients of information and does not sufficiently stimulate inquiry or reasoning (Ahzari & Akmam, 2025; Nurjanah et al, 2024). Consequently, students may master formulas and definitions without truly understanding the underlying principles or being able to apply them in novel contexts. The gap between the objectives of physics education and the reality of classroom practice highlights the need for innovative approaches that integrate interactive learning media to foster deeper understanding and critical thinking.

Technology-enhanced learning media have emerged as promising solutions to address these challenges. The integration of digital applications in the classroom can provide new ways of representing abstract physics concepts, thereby supporting students' comprehension and engagement. According to Andriani (2016), innovative media that combine visual, interactive, and contextual elements can help students connect theoretical knowledge with real-world experiences, making learning more meaningful. By employing interactive technologies, students are not only motivated but also encouraged to actively participate in constructing knowledge, an approach that strengthens their reasoning and problem-solving abilities. In this regard, digital tools such as augmented reality (AR) hold significant potential for transforming physics instruction (Hidajat, 2024).

Several empirical studies have shown that technology-based interventions can enhance students' learning outcomes and higher-order skills. For instance, Sari et al. (2020) found that the use of digital media in science classes improved students' analytical and interpretative skills by providing representations that bridged abstract theory and observable practice. In physics education, such representations are particularly important, as many concepts, such as forces, fields, and atomic interactions, cannot be directly observed. Through digital visualization, students can engage more actively with content, ask questions, and critically evaluate scientific ideas. This interactivity aligns with the pedagogical goal of moving beyond rote learning toward inquiry-driven education.

In recent years, AR has been identified as one of the most innovative technologies in education because it overlays digital objects onto the real environment, enabling learners to interact with both simultaneously. A meta-analysis published in Education and Information Technologies found that AR applications in STEM education consistently enhance learners' engagement, cognitive performance, and conceptual understanding by providing immersive and interactive experiences (Hidayat & Wardat, 2023; Zhang et al, 2022). Volioti et al. (2022) emphasized that AR applications in science classrooms significantly contribute to the development of students' critical and creative thinking by creating immersive experiences that promote exploration and reasoning. In physics instruction, AR can be used to model complex systems, simulate phenomena that are difficult or dangerous to reproduce in school laboratories, and provide students with opportunities to test hypotheses in interactive ways (Luthfi et al, 2025). These affordances directly support the cultivation of critical thinking, as students are required to interpret virtual models, analyze patterns, evaluate outcomes, and draw inferences based on their observations.

Despite the growing body of research on digital media in education, there remains a lack of empirical evidence focusing specifically on the impact of AR on critical thinking skills in the context of high school physics. Many studies have examined the influence of AR on motivation, attitudes, or conceptual understanding, but fewer have addressed its role in fostering higher-order skills. This gap underlines the importance of conducting systematic investigations that measure not only achievement but also the dimensions of critical thinking, including interpretation, analysis, evaluation, and inference. By addressing this gap, the present study seeks to contribute to the literature by offering empirical insights into how AR-based learning media affect students' critical thinking in physics.

The purpose of this study is to examine the effect of AR-based learning media on the critical thinking skills of high school students in physics classes. Specifically, it employs a quasi-experimental, posttest-only nonequivalent control group design to compare the performance of students taught using AR-enhanced lessons with those receiving conventional instruction. The novelty of this study lies in its focus on critical thinking as the primary outcome, rather than solely on conceptual mastery or motivational factors. By doing so, it provides a more comprehensive perspective on the pedagogical value of AR. The findings are expected to enrich the literature on technology-enhanced physics education and provide practical implications for teachers and policymakers in developing instructional strategies that not only improve conceptual understanding but also foster the critical competencies required for success in science and beyond.

II. METHODS

This study employed a true experimental design with a posttest-only nonequivalent control group, a design commonly adopted in educational research where random assignment is not feasible due to institutional or classroom constraints (Campbell & Stanley, 2015). In the present research, two intact classes of Grade XII students were selected purposively to serve as the experimental and control groups. The experimental group (XII-5, 32 students) received physics instruction using AR–based media, whereas the control group (XII-4, 33 students) was taught using conventional methods. The purposive sampling strategy was deemed appropriate because it allowed the researcher to select classes with comparable characteristics and ensured the feasibility of implementation in the school setting.

The instructional content targeted in this study was electrostatics, a subject known for its high level of abstraction and conceptual difficulty among high school students. In the experimental class, the AR-based media—PyLo-AR—was implemented to visualize abstract concepts such as Coulomb's law and atomic models by superimposing three-dimensional digital objects onto the physical learning environment. Figure 1 illustrates an example of the AR interface as it was applied during classroom instruction. The application allowed students to observe and manipulate virtual charges and fields through mobile devices, thereby creating an immersive learning experience that bridged theory with tangible representations. By contrast, the control group followed the school's standard instruction involving teacher explanation, whiteboard illustrations, and textbook exercises. The same teacher taught both groups to minimize the teacher effect as a confounding variable.

Figure 1. Augmented reality application (PyLo-AR) used in the experimental class

The instrument used to measure students' performance consisted of a critical thinking test in the form of open-ended essay items aligned with established indicators of critical thinking: interpretation, analysis, evaluation, and inference (Facione, 2015). The original version of the instrument contained eight items. However, after expert validation and a small-scale trial, seven items were retained for the posttest to ensure reliability and appropriateness for the target population. Validity was examined through expert judgment involving physics education specialists, who reviewed the items for content relevance, clarity, and alignment with learning objectives. Reliability was calculated using Cronbach's alpha, yielding a coefficient that fell within the "high" category according to standard criteria (Fraenkel & Wallen, 2019).

Data collection occurred after the completion of the instructional intervention, with both groups undertaking the same posttest under controlled conditions. Because the design did not include a pretest, comparisons between the two groups relied solely on posttest data. This limitation, acknowledged in the design, reflects the inherent challenge of quasi-experiments where intact classes are compared without randomization (Shadish et al., 2002). Nevertheless, this approach is widely considered valid for educational settings where pre-intervention testing may influence learning outcomes or when pretest administration is logistically constrained (Cook & Campbell, 1979).

For the analysis, both descriptive and inferential statistics were employed. Descriptive statistics provided measures of central tendency (mean, median) and variability (standard deviation) to capture the overall distribution of students' scores in each group. Inferential statistics were conducted to test whether the observed differences between the experimental and control groups were statistically significant. Before hypothesis testing, assumptions of normality and homogeneity of variance were evaluated. The Shapiro–Wilk test was used to examine normality, yielding significance values greater than 0.05 for both groups, thus confirming that the data approximated a normal distribution (Razali & Wah, 2011). Homogeneity of variance was tested using Levene's test, which also indicated nonsignificant results, thereby meeting the assumption for the independent samples t-test.

Several procedures strengthened the methodological rigor of this study. First, the use of validated instruments ensured that the test items measured critical thinking reliably and consistently. Second, the same teacher implemented both instructional approaches to minimize variability in teaching style. Third, the use of established statistical procedures for assumption testing and hypothesis testing provided a sound basis for interpreting the results. However, the study also recognized limitations inherent in its design. The absence of a pretest made it impossible to fully account for initial differences in critical thinking skills between the two groups. Furthermore, the purposive sampling strategy restricted the generalizability of the findings beyond the specific school context. These methodological considerations are consistent with discussions in the literature that highlight both the strengths and limitations of quasi-experimental research in educational settings (Creswell & Creswell, 2018).

III. RESULTS AND DISCUSSION

The results of the study are presented through descriptive and inferential analyses to determine the effect of AR–based media on students' critical thinking skills in physics. Descriptive analysis was first employed to examine the mean, standard deviation, and categorization of students' scores, followed by inferential statistics to test the significance of differences between the experimental and control groups.

Table 1 presents the descriptive statistics of students' critical thinking scores for both groups. The experimental group, which received AR-based instruction, obtained a mean score of 14.56 with a standard deviation of 2.031. In contrast, the control group, taught using conventional methods, achieved a mean score of 12.94 with a standard deviation of 1.952. The minimum and maximum values indicate that students in the experimental group consistently performed at a higher level than those in the control group. Based on the classification criteria, the majority of students in the experimental group fell into the "high" and "very high" categories. In contrast, students in the control group were distributed more heavily in the "moderate" range.

Table 1. Descriptive statistics of students' critical thinking scores

Group	N	Mean	SD	Min	Max
Experimental	32	14.56	2.03	11	19
Control	33	12.94	1.95	9	17

To illustrate the distribution of scores more clearly, Figure 2 displays the histogram of critical thinking scores in the experimental group, while Figure 3 shows the distribution for the control group. Both histograms approximate a normal distribution, but the experimental group exhibits a higher concentration of students in the upper ranges, reflecting stronger performance. By contrast, the control group shows clustering around lower values, with fewer students achieving high scores.

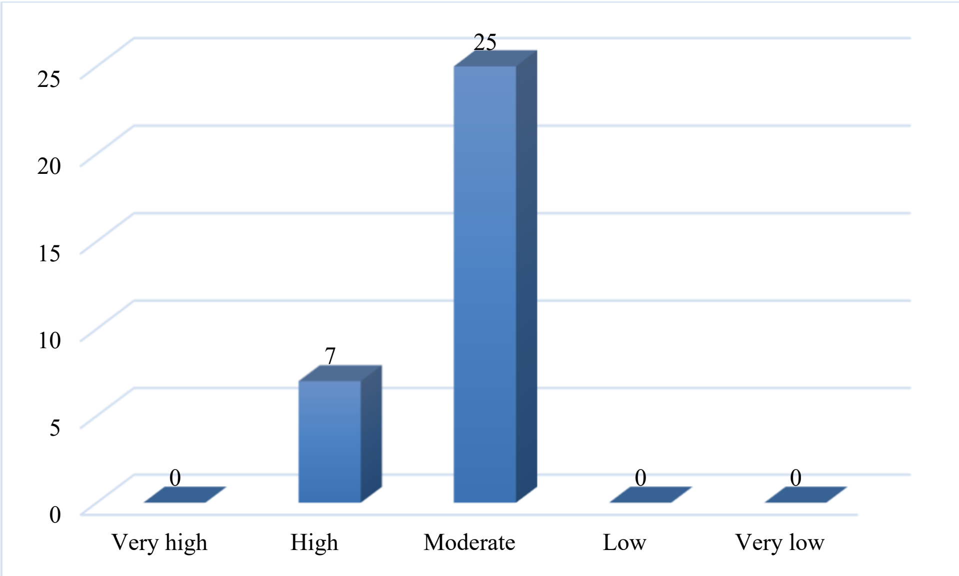

Figure 2. Histogram of students' critical thinking scores in the experimental group

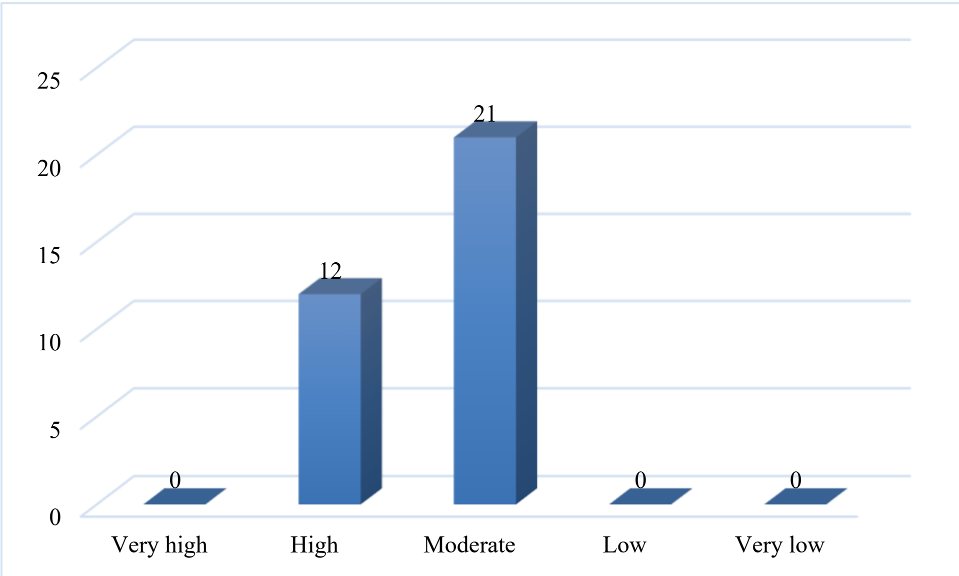

Figure 3. Histogram of students' critical thinking scores in the control group

Before conducting inferential analysis, the assumptions of normality and homogeneity of variance were tested. Results of the Shapiro–Wilk test indicated that both the experimental group ($p = 0.087$) and the control group ($p = 0.054$) met the assumption of normality, as all significance values were greater than 0.05. Levene's test for homogeneity produced $p = 0.263$, suggesting that variances between the two groups were equal. These findings justified the application of the independent samples t-test.

The independent samples t-test revealed a statistically significant difference between the groups, as presented in Table 2. The p-value of 0.002 ($p < 0.05$) confirmed that the higher mean score of the experimental group was not due to random variation but rather reflected the positive effect of AR-based media on students' critical thinking performance.

Table 2. Normality test results of the Shapiro-Wilk

Class		**Shapiro Wilk**		
		Statistics	df	Sig.
Results	Post-test Control	.944	33	.087
	Post-test experiment	.935	32	.054

This study uses a homogeneity test to see whether two or more groups of sample data have homogeneous variance and are suitable for use. Data is declared homogeneous if the significance value is > 0.05. Based on the homogeneity test of variance using SPSS, a significance value of 0.197 was obtained, indicating that the data are homogeneous.

Table 3. Results of Levene's test for homogeneity of variance

Test of Homogeneity of Variance					
		Levene Statistics	df1	df2	Sig.
Results	Based on Mean	1.703	1	63	.197
	Based on Median	1.209	1	63	.276
	Based on Median and with adjusted df	1.209	1	61.091	.276
	Based on the trimmed mean	1.656	1	63	.203

Hypothesis testing in this study uses the t-test with the help of SPSS. The results of the t-test will show whether or not there is a difference in scores between the experimental group and the control group. Data is considered different, or there is a difference between two treatments, if the significance value is below 0.05. The results of the T test show a significance value of 0.0002, which means <0.05, so that the data in the control and experimental classes are different.

Table 4. Results of an independent samples t-test for the experimental and control groups

Independent samples test										
Levene's test for equality of variances				t-test for equality of means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Result	Equal variances assumed	1.703	.197	-3.286	63	.002	-1.623	.494	-2.610	-.636
	Equal variances not assumed			-3.284	62.683	.002	-1.623	.494	-2.611	-.635

The findings of this study revealed that augmented reality (AR)–based instruction produced a significant improvement in students' critical thinking skills compared to conventional methods. The experimental group consistently outperformed the control group, as reflected in higher mean scores and a more favorable distribution across performance categories. These results indicate that AR is an effective pedagogical tool in physics education, particularly for supporting higher-order thinking skills. Similar outcomes have been documented by Nurjanah et al. (2024) and Volioti et al. (2022), who emphasized that technology-enhanced environments facilitate students' engagement and cognitive development by offering more interactive and meaningful learning experiences.

One important contribution of AR lies in its ability to represent abstract physics concepts, such as electrostatics, in a more concrete and accessible way. By overlaying digital objects in the real environment, students can manipulate models of charges and electric fields that are otherwise invisible to direct perception. This finding is consistent with Hidayatunnajah (2021), who reported that AR increases student motivation and facilitates deeper understanding, and with Chang et al. (2022), who demonstrated that AR-based media create immersive learning environments that support the development of critical and creative thinking skills. The present study, therefore, strengthens the growing consensus that AR can reduce misconceptions and promote conceptual clarity in physics classrooms.

The use of AR also resonates with the findings of Hidajat (2024) and Azzahra et al. (2024), who noted that integrating digital tools into science education improves both achievement and students' reasoning skills. Likewise, Lubis et al. (2025) and Martawijaya et al. (2023) showed that interactive applications lead to higher learning gains by encouraging exploration and interpretation. In line with these studies, our findings indicate that students in the AR group demonstrated stronger performance in interpretation and evaluation, two key dimensions of critical thinking. This suggests that AR fosters students' ability to make sense of information and critically assess scientific phenomena.

The effectiveness of AR in enhancing reasoning has also been emphasized by Siregar et al. (2023) and Zulkarnaen et al. (2025), who observed that AR-supported lessons provide scaffolds that help learners analyze problems systematically. Arni (2025) similarly found that students engaged with AR tasks developed higher levels of cognitive engagement compared to traditional classes. These observations are consistent with the present results, where AR students not only achieved higher mean scores but also demonstrated more consistent performance, as indicated by the narrower standard deviation compared to the control group.

The findings also align with broader discussions in recent literature. Nasar et al. (2025) and Herliana et al. (2025) highlighted that immersive media such as AR, encourage collaboration and discussion, which are essential for critical thinking. Hahn et al. (2025) and Zhang et al. (2022) further noted that technology-mediated learning fosters students' ability to evaluate claims and construct arguments, a dimension strongly linked to critical reasoning. This study extends those findings by showing that AR contributes not only to motivation and engagement but also to measurable gains in the interpretation, evaluation, and inference aspects of critical thinking.

Contextual evidence from local studies also supports these results. Rahmat et al. (2023) and Akhiruyanto and Yudhistira (2024) found that AR-based modules increased student activity and enhanced cognitive outcomes in physics topics that were previously considered difficult. Luthfi et al. (2025) and Zufahmi et al. (2025) also observed improvements in students' reasoning and evaluative skills through AR-based interventions. Likewise, Azzahra et al. (2024) and Fariyani et al. (2025) reported that the integration of digital simulations with classroom instruction encouraged critical inquiry and deeper problem-solving. The present study, therefore, confirms that AR has robust potential for application in Indonesian physics classrooms, as it strengthens both engagement and higher-order skills.

The consistency of these results is further reinforced by the studies of Pujono et al. (2024) and Sianipar et al. (2025), who highlighted the effectiveness of AR in broadening students' capacity for inference and judgment, as well as by Mor et al. (2025), who argued that AR-based environments support metacognitive processes central to critical reasoning. Similarly, Supriyadi et al. (2023) and Fatonah et al. (2024) noted that AR enhances collaboration, creativity, and evaluation, leading to holistic improvements in students' learning outcomes. Together, these findings provide convergent evidence that the integration of AR in physics learning contexts is not only beneficial for content mastery but also transformative for higher-order cognitive development.

IV. CONCLUSION AND SUGGESTION

The results of this study demonstrate that integrating AR–based media into physics instruction has a significant positive effect on students' critical thinking skills. Students in the experimental group outperformed their peers in the control group, achieving higher mean scores and a more favorable distribution across performance categories. The findings confirm that AR can effectively support the development of critical thinking indicators, interpretation, analysis, evaluation, and inference by making abstract physics concepts more concrete and engaging. This study, therefore, provides empirical evidence that AR-based instruction can enhance both the depth and quality of student learning in physics classrooms.

Despite its promising outcomes, the study has several limitations. The quasi-experimental design without random assignment and the absence of pretest data fully restricts the ability to control for initial differences between groups. In addition, the research was limited to a single school, a relatively small sample size, and one physics topic, which narrows the generalizability of the findings. Future studies should address these limitations by employing larger and more diverse samples, using pretest–posttest designs, and exploring multiple physics topics to capture broader patterns of AR's impact. Nonetheless, the contribution of this study lies in highlighting the role of AR not only in improving conceptual understanding but also in strengthening students' critical thinking skills. This offers valuable insights for educators and policymakers seeking to advance the quality of physics education in the twenty-first century.

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